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A PRELIMINARY ANALYSIS OF THE APS CROTCH DESIGN (*)

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1. Summary

A preliminary design analysis of the absorber plate of the proposed crotch for the APS bending magnet radiation is presented. Various design aspects including thermal and structural considerations, material selection, geometry, and cooling method are discussed and a number of recommendations are made.

2. Introduction

Bending magnet (BM) radiation is an intense beam of radiation generated by each of the 80 dipole magnets in the APS storage ring [1]. There are two bending magnets per sector of the ring and between them a straight section where an insertion device (ID, wiggler or undulator) is used to generate powerful concentrated beams of radiation (Figure 1). Only the BM upstream of an ID is used as a radiation source.

Most of the synchrotron radiation generated by the bending magnets are absorbed in chambers referred to as the crotch, so named for its location near the point of separation of x-ray and electron beam (Figure 2). Each of the 80 bending magnets produces a fan of radiation with opening angles of about 80 mrad (4.5°) horizontally and 0.2 mrad vertically. The crotch of the bending magnet downstream of an ID absorbs all the BM radiation and passes the ID radiation. The crotch of the bending magnet upstream of an ID absorbs all but about 6 mrad of BM radiation.

The distance from the point on the storage ring at which BM radiation is generated to the absorbing wall of the crotch varies from about 1.9 to 3.7 m (see Figure 2). The BM radiation flux varies slowly in the horizontal direction (i.e., in the plane of the storage ring) and follows a nearly Gaussian profile vertically (Figure 3). The footprint of the beam on the absorber wall of the crotch at normal incidence is about 0.5 mm vertically and 13 cm horizontally.

The normal incidence flux distribution of the BM radiation [in kW/m^2] at the absorber wall of the crotch for a 300 mA ring current can be written as

$$q''(y,z) = \frac{2.345\times10^6}{\ell^2(z)}\, e^{-\frac{1}{2}\left(\frac{y}{\sigma(z)}\right)^2} \qquad (1.a)$$

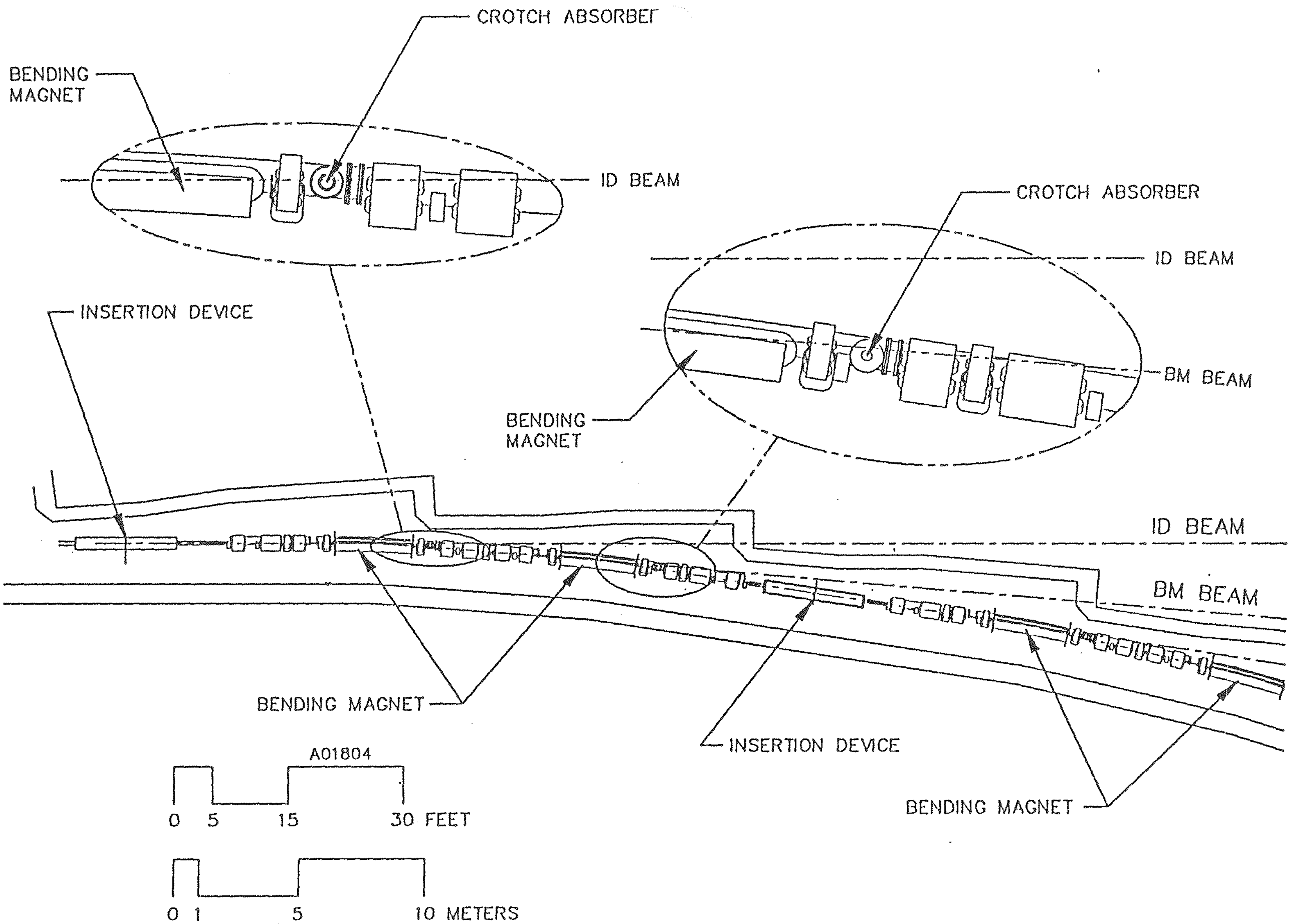
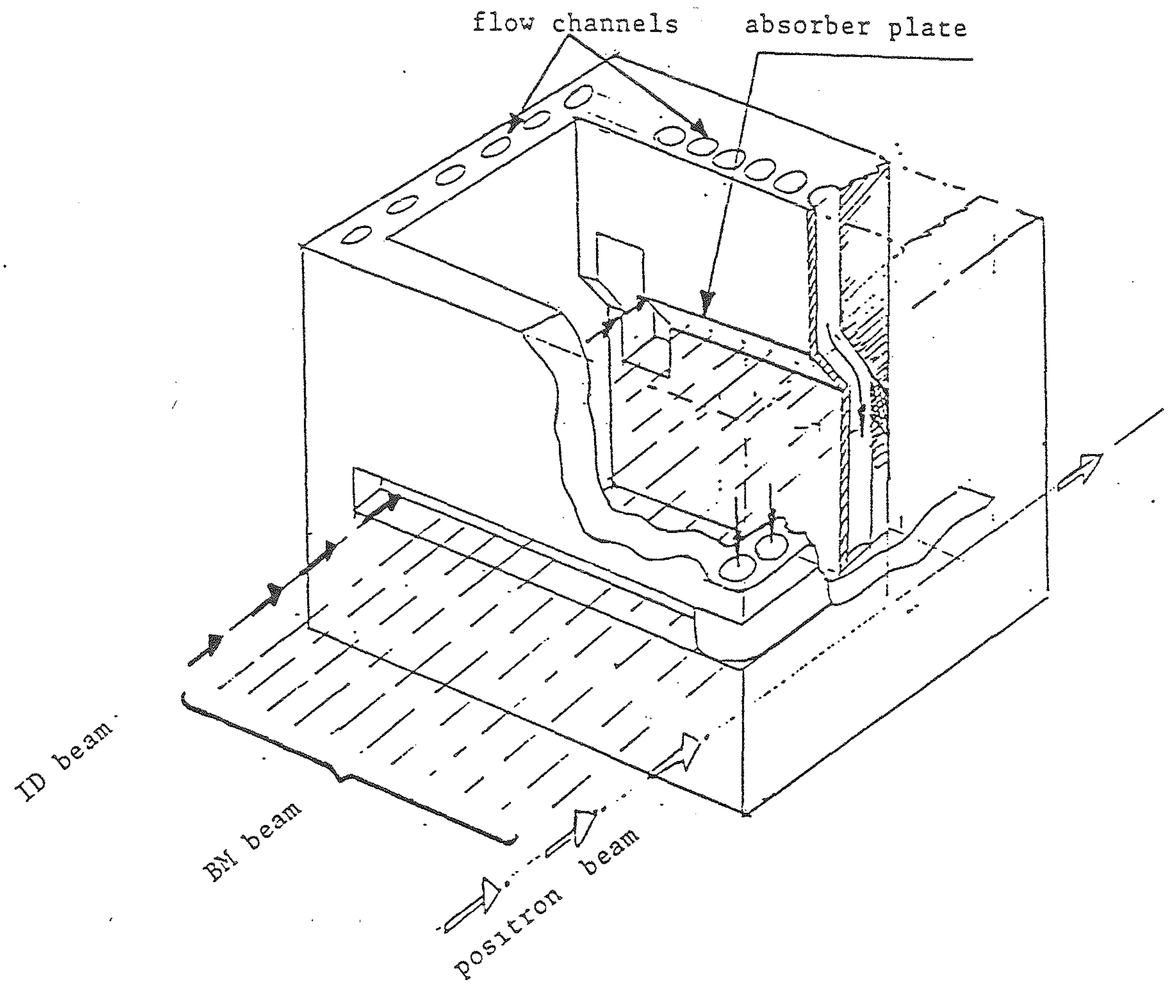


Figure 1: A segment of the storage ring consisting of two sectors. Each sector includes an insertion device and two bending magnets. The radiation from the bending magnet downstream of an ID (shown enlarged on the left) is all absorbed by its crotch, while a small portion of the bending magnet radiation from the bending magnet upstream of an ID (shown enlarged on the right) is passed through.



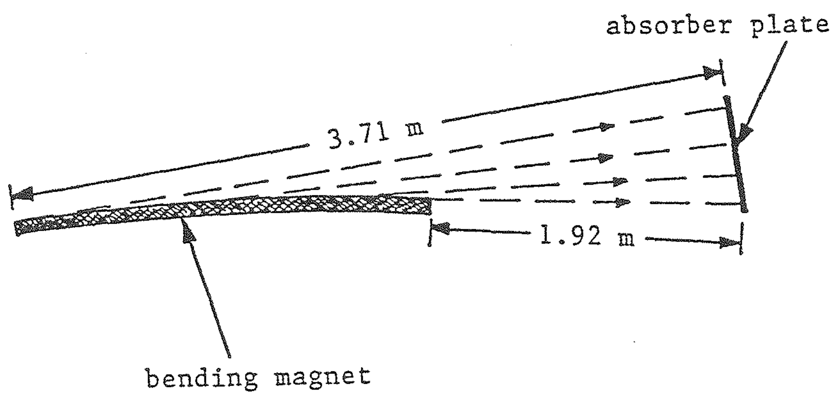


Figure 2: A conceptual configuration of the crotch chamber which absorbs the bending magnet radiation and passes ID and positron beams (above), and bending magnet radiation absorbed by the crotch absorber plate (below).

above y and z are the horizontal and vertical coordinates, respectively, (see Figure 3), $\ell(z)$ is the distance (in meters) between the points of generation (at the BM) and absorption (on the crotch) of a BM ray, and $\sigma(z)$ is the standard deviation of the vertical Gaussian distribution (in meters) at the wall given by

$$\sigma(z) = \frac{\ell(z)}{2.253 \times 10^4} \tag{1.b}$$

The horizontal (vertically integrated) power distribution in kW/m is

$$q'(z) = \frac{2.345\times10^6}{\ell^2(z)} \int_{-\infty}^{\infty} e^{-\frac{1}{2}\left(\frac{y}{\sigma(z)}\right)^2} dy$$

which upon substituting $\sigma(z)\sqrt{2\pi}$ for the integral term and simplifying, gives

$$q'(z) = \frac{260.8}{\ell(z)} \tag{2}$$

Values of $\ell(z)$ as a function of z are listed in Table 1. From Eq. 2 and the range of ℓ in Table 1, it is evident that the horizontal distribution of incident beam power at the absorber wall of the crotch ranges from a maximum of 1358 W/cm (at z = 0) to a minimum of 703 W/cm (at z = 13 cm). The peak heat flux incident on the crotch (at y=z=0) from Eq. 1 is 636 W/mm^2.

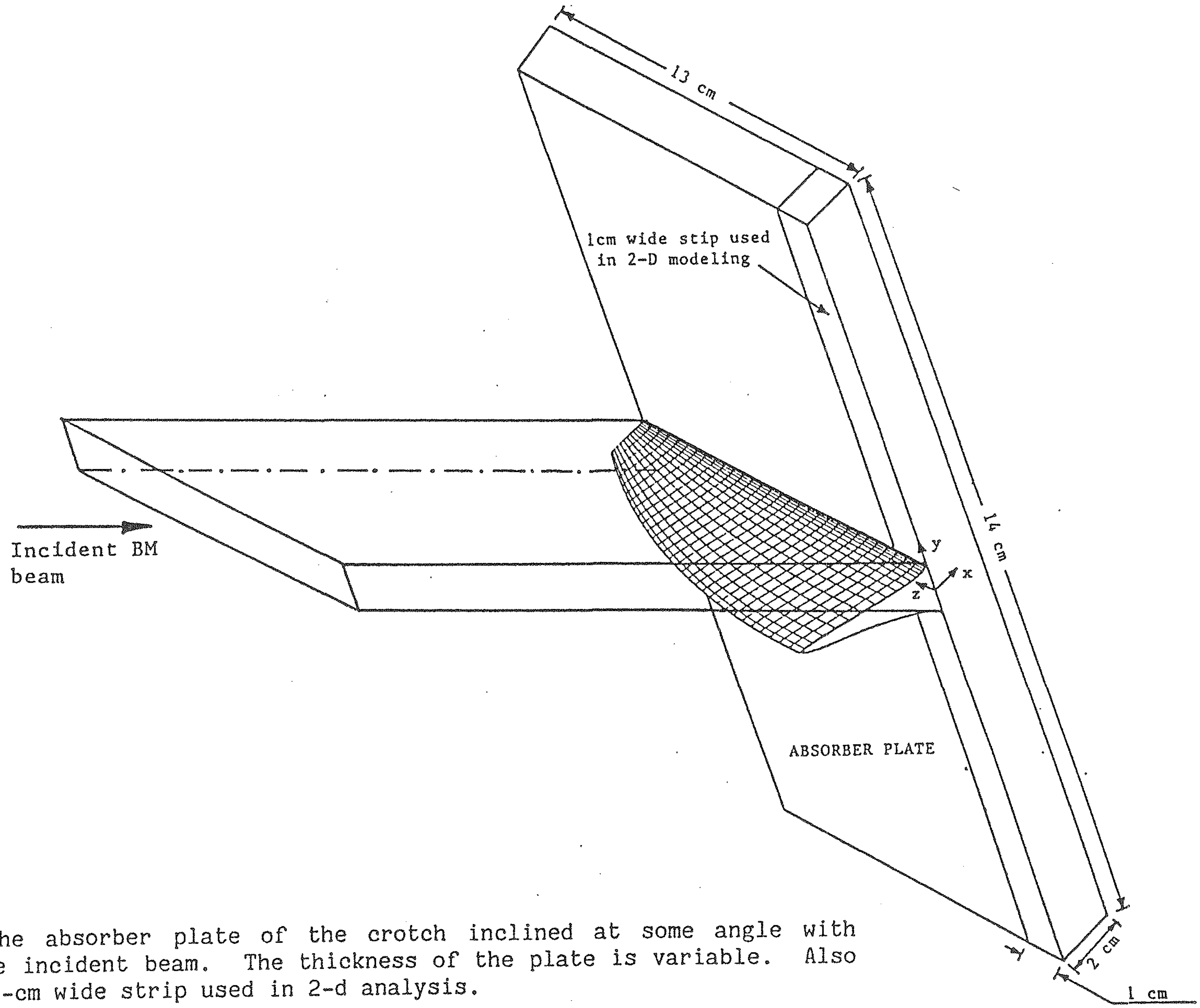


Figure 3: The absorber plate of the crotch inclined at some angle with respect to the incident beam. The thickness of the plate is variable. Also shown is the 1-cm wide strip used in 2-d analysis.

TABLE 1

Variation of distance between source and absorber plate as a function of z

z (cm)	ℓ (z) (m)
0	1.92
2	2.11
3	2.45
4	2.61
5	2.75
6	2.89
7	3.02
8	3.15
9	3.27
10	3.38
11	3.50
12	3.61
13	3.71

3. The Crotch Problem

The removal of the intense and localized heat load generated by the impinging bending magnet radiation on the absorber wall of the crotch while maintaining thermal and structural integrity of the crotch during steady state and cyclic mode of operation is referred to as the crotch problem. In addition, photo desorption and outgassing of the radiated/heated walls which are coupled with the thermal problem through their dependence on the extent of the radiated area, surface temperature, and scattering from the crotch edges are integral parts of the problem. The choice of the crotch material, surface, and geometric configuration of the crotch in connection with photodesorption and outgassing is not discussed in this preliminary report [2], nor is the absorption and scattering of x-ray radiation from the crotch edges. This preliminary study only deals with the absorber plate of the crotch where most of the BM radiation is absorbed.

4. Modeling of the Crotch

For the purpose of this preliminary thermal analysis it is quite adequate to model only the absorbing wall of the crotch. In particular, since all conductive interfaces between the plate and adjacent members of the crotch are replaced by idiabatic boundaries, the results of this thermal analysis are conservative. The conduction at these boundaries leads to an overall reduction in the temperature of the absorber wall reported here.

A further conservative simplification is to treat the plate as a two-dimensional medium. The plate is assumed to be horizontally infinite in extent and subject to the maximum heat load per unit length in that direction. Thus, a vertical strip of the absorbing plate with the arbitrary horizontal extent of unity (1 cm here) is modeled (Figure 3). The incident beam is thus uniform horizontally and Gaussian vertically. From Eq. 2, the total power of this incident beam (at $z = 0$) is 1358 W and its vertical standard deviation σ (at $z=0$) is 0.0085 cm (Eq. 1.b). We note, however, that at the other end of the beam footprint (i.e., at $z=13$ cm), the total power per horizontal centimeter and the standard deviation of its vertical profile are 703 W and 0.0165 cm respectively. Therefore, the incident heat flux at that end is about one-fourth of the maximum value (at $z=0$) because it has about half the power and twice the vertical spread. In a more detailed study, and in particular in connection with establishing the required coolant flow rate this flux distribution must be taken into account.

5. Crotch Material Selection

The extremely high heat flux of the bending magnet radiation deposited on the absorber wall of the crotch generally leads to unacceptably high wall temperature even with highly conductivity crotch materials such as silver and copper. Upper bound on the absorber plate temperature must be imposed to satisfy the requirements for (a) maintaining the mechanical strength of the wall, (b) safe operation of the crotch, (c) acceptable thermal and photon induced desorption levels, and (d) viability of water as the coolant fluid.

The criterion we adapt in the design of the crotch is that the maximum absolute temperature of the absorber wall should be between one half and one third of the melting temperature of the material. For copper with melting temperature of 1358 K, a maximum allowable temperature of 300-350°C is assumed.

In order to reduce the high temperatures in the absorber plate, for a given cooling scheme, it is necessary to increase the spread and diffusion of the incident BM radiation in the plate. This can be achieved by (a) selecting a highly conductive material to conduct the heat efficiently, (b) incline the absorber wall with respect to the incident beam so as to spread the beam over a larger area, and (c) utilize a diathermanous (semi-transparent) material to gradually absorb the incident beam. Furthermore, plate configuration as well as the method and the efficiency of the convective cooling scheme represented by an overall (average) heat transfer coefficient affect the maximum surface temperature of the plate. Liquid metal and boiling water owing to their high heat transfer coefficients, can reduce the overall plate temperature considerably.

In an attempt to reduce the absorber plate temperature, in the following sections the effect of each of the above factors on the maximum temperature in the plate is examined. Simple cartesian one-dimensional models are used to demonstrate the essential features of the problem without undue complexity.

6. Effects of Thermal Conductivity and Cooling Efficiency on the Absorber Plate Temperature

Consider a slab of thickness L heated on one side with a uniform flux q" and cooled on the other as shown in Figure 4a. The material has a thermal conductivity k. Heat transfer coefficient is h and the fluid bulk temperature is T_∞. The temperature in the slab is given by

$$T(x) - T_\infty = -\frac{q''}{k} x + q'' \left(\frac{1}{h} + \frac{L}{k}\right) \tag{3.a}$$

The maximum temperature $T_{max} = T(0)$ is

$$T_{max} - T_\infty = q''\left(\frac{1}{h} + \frac{L}{k}\right) \tag{3.b}$$

$$T(L) - T_\infty = \frac{q''}{h} \tag{3.c}$$

$$\Delta T = T(0) - T(L) = q'' \frac{L}{k} \tag{3.d}$$

From Eq. (3.b) it is apparent that a reduction in the maximum temperature can be affected by reducing the heat flux, reducing the thermal resistance (1/h + L/k) of the system, or by lowering the fluid bulk temperature. For a given slab and heat flux, a higher value of h reduces the maximum temperature. This reduction, however, may or may not be significant depending on the relative values of the 1/h and L/k terms. For example, for a 2 cm water-cooled copper plate (h = 1 W/cm^2-K, k = 4 W/cm-K), we have

$$\frac{1}{h} = 1; \quad \frac{L}{k} = \frac{1}{2}$$

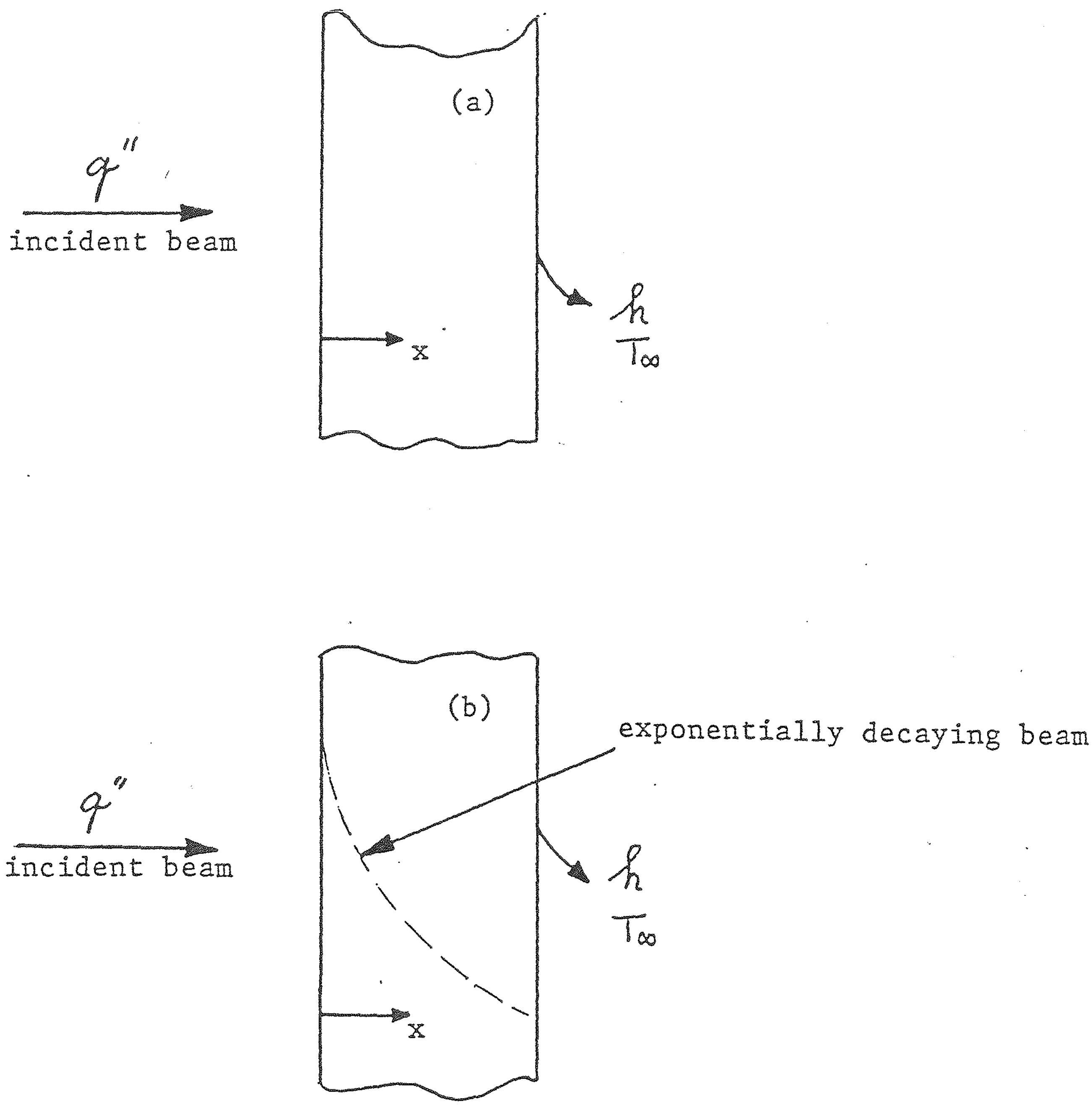


Figure 4: One-dimensional slab of (a) an opaque and (b) a diathermanous material used in the analysis. A uniform x-ray beam is incident on one side of the slab and the generated heat is convected away on the other side. In case b, the x-ray beam is gradually absorbed in the slab.

which are, respectively, the resistance to the transfer of heat by the copper block and by water. A doubling of h will only reduce the total thermal resistance by one-third and the maximum wall temperature by a similar amount. Replacing copper with a less conductive material such as aluminum ($k = 2.4$ w/cm-K), in the example above, increases thermal resistance by about 20% and the maximum wall temperature by a similar amount. It is also noteworthy that the temperature of the cooled wall (Eq. 3.c) is independent of the plate material, and for given q" and T_∞ values it depends on h exclusively. The temperature gradient across the slab is related to q" and k only.

7. Effects of a Diathermanous Material on the Absorber Plate Temperature

A diathermanous material absorbs the incident radiation at successive depths and in effect helps diffuse the incident radiative heat in the material. Such a material can be thought of as having a generically superior heat conductivity in the direction of the incident x-ray beam.

In order to examine how a diathermanous material used as the crotch plate leads to a lower plate temperature, consider a slab of such a material of thickness L, conductivity k, and subjected to an incident radiative flux q" on one side and cooled on the other side by water (Figure 4.b).

Let us assume an overall exponential transmission profile for the BM radiation in the slab of the form e^{-ax} where "a" is the attenuation constant*. The absorption per unit volume is

$$q''' = q'' \, a \, e^{-ax} \tag{4}$$

*The spectrally integrated transmission profile of BM radiation in beryllium obtained from the Photon program fits the curve $e^{-a\sqrt{x}}$ much more closely.

Solving the diffusion equation yields the following temperature distribution in the semi-transparent plate:

$$T(x) - T_\infty = \frac{q''}{ka} \left(e^{-aL} - e^{-ax}\right) + q'' \left[\frac{(L-x)}{k} - \frac{(e^{-aL}-1)}{h}\right] \tag{5.a}$$

The maximum temperature $T_{max} = T(0)$ is given by

$$T_{max} - T_\infty = q'' \left(\frac{L}{kC_1} + \frac{1}{hC_2}\right) \tag{5.b}$$

and

$$T(L) - T_\infty = \frac{q''}{hC_2} \tag{5.c}$$

$$\Delta T = T(0) - T(L) = q'' \frac{L}{kC_1} \tag{5.d}$$

where

$$C_1 = \frac{aL}{aL - 1 + e^{-aL}}; \qquad C_2 = \frac{1}{1 - e^{-aL}} \tag{5.e}$$

The effect of the gradual absorption of radiation can be seen by comparing Eqs. (3) and (5). From Eqs. (3.a) and (5.a) it is clear that the semi-transparency of the material leads to apparent enhancements in the thermal conductivity (by a factor $C_1>1$) and convection efficiency (by a factor $C_2>1$).

As an example, the APS bending magnet radiation loses about three-fourths of its power in passing through 2-cm of beryllium slab. Thus, letting e^{-aL} = 1/4 the enhancement factors C_1 and C_2 are

$C_1 = 2.18$

$C_2 = 1.33$

In the present one-dimensional model, this enhanced "conductivity" resulting from gradual attenuation of the beam is somewhat offset by the lower thermal conductivity of beryllium. High conductivity copper is twice as conductive as beryllium, but absorbs the incident BM radiation almost at the surface. The absorber plate, however, need not be an all beryllium slab; a piece of brazed Be mounted on or inserted onto a copper plate will diffuse the impinging radiation while allowing the dissipation of the heat by the highly conductive copper plate.

We note that a one-dimensional model of the absorber wall formulated in polar coordinates with origin at the source will represent the crotch problem more accurately. The essential features, however, can be shown using the simple cartesian model used here.

8. Effect of Absorber Plate Inclination on the Plate Temperature

Inclination of the absorber plate will spread the beam over a larger area. The incident flux is thus reduced and so is the maximum temperature of the plate as seen from Eqns. 3 or 5. The plate can be inclined horizontally, vertically, or both. The absorber plate need not be flat; it can have a concave or convex profile to spread the beam. In fact, a brazed beryllium piece with a crescent-shaped cross-section on a copper plate may be an attractive option.

9. The Temperature of the Cooled Surface of the Absorber Plate

For single phase convective heat transfer, the maximum temperature of the wall adjacent to the coolant must not exceed the saturation temperature of the fluid at the prevailing pressure. Should the temperature exceed this value, boiling can be prevented by reducing the fluid inlet temperature (e.g., using chilled water) or increasing the fluid pressure. The saturation temperature of water at various temperatures is listed in Table 2.

TABLE 2

Saturation Temperature of Water at Various Pressures

P (atm.)	T(°C)
1	100
2	120
3	136
4	144
5	152
6	159
7	165
10	180

In two phase heat transfer regime, the excess temperature (the amount by which wall temperature exceeds the saturation temperature of the fluid at the prevailing pressure) must be below the critical flux excess temperature of the coolant. For water pool boiling, this excess temperature is approximately 35°C and the corresponding critical heat flux is of the order of 1 MW/m^2.

From the earlier one-dimensional analysis (Eqs. 3.c or 5.c) it is seen that for given incident heat flux and wall configuration, the temperature of the cooled surface is primarily dependent on the heat transfer coefficient and independent of the thermal conductivity of the wall material. Therefore, the heat transfer coefficient is the determinant factor affecting the temperature of the cooled surface of the absorber plate.

10. Finite Element Modeling of the Absorber Plate

The intense and localized bending magnet radiation incident upon the absorber wall of the crotch sets up very large local thermal gradients requiring very fine meshing and thus a large number of elements about the beam

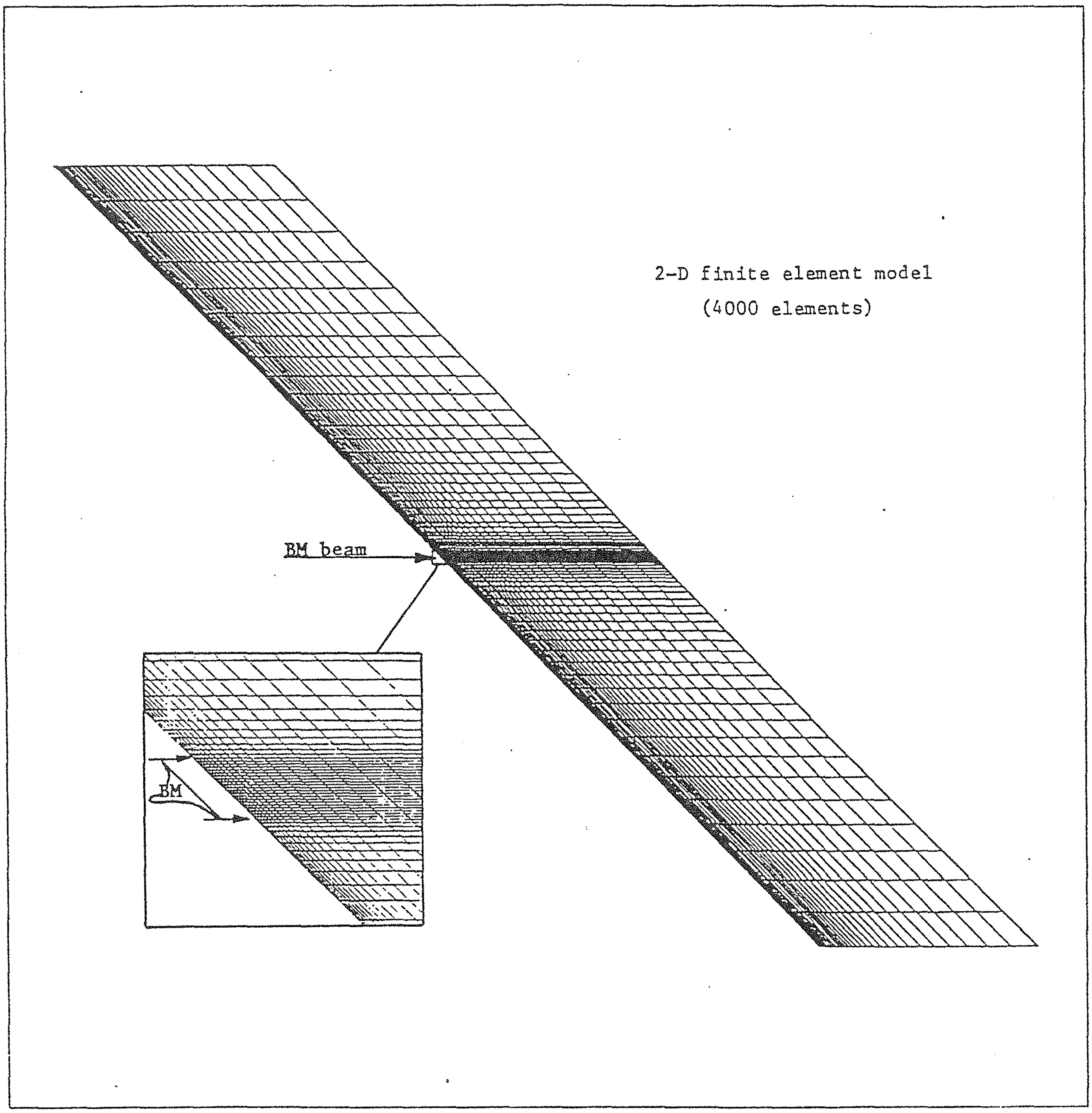


Figure 5: Typical meshing scheme used in the finite element analysis of an absorber copper plate. The width of the strip modeled is 1 cm (into the paper). In the case shown, the plate in inclined at 45° with respected to the incident beam.

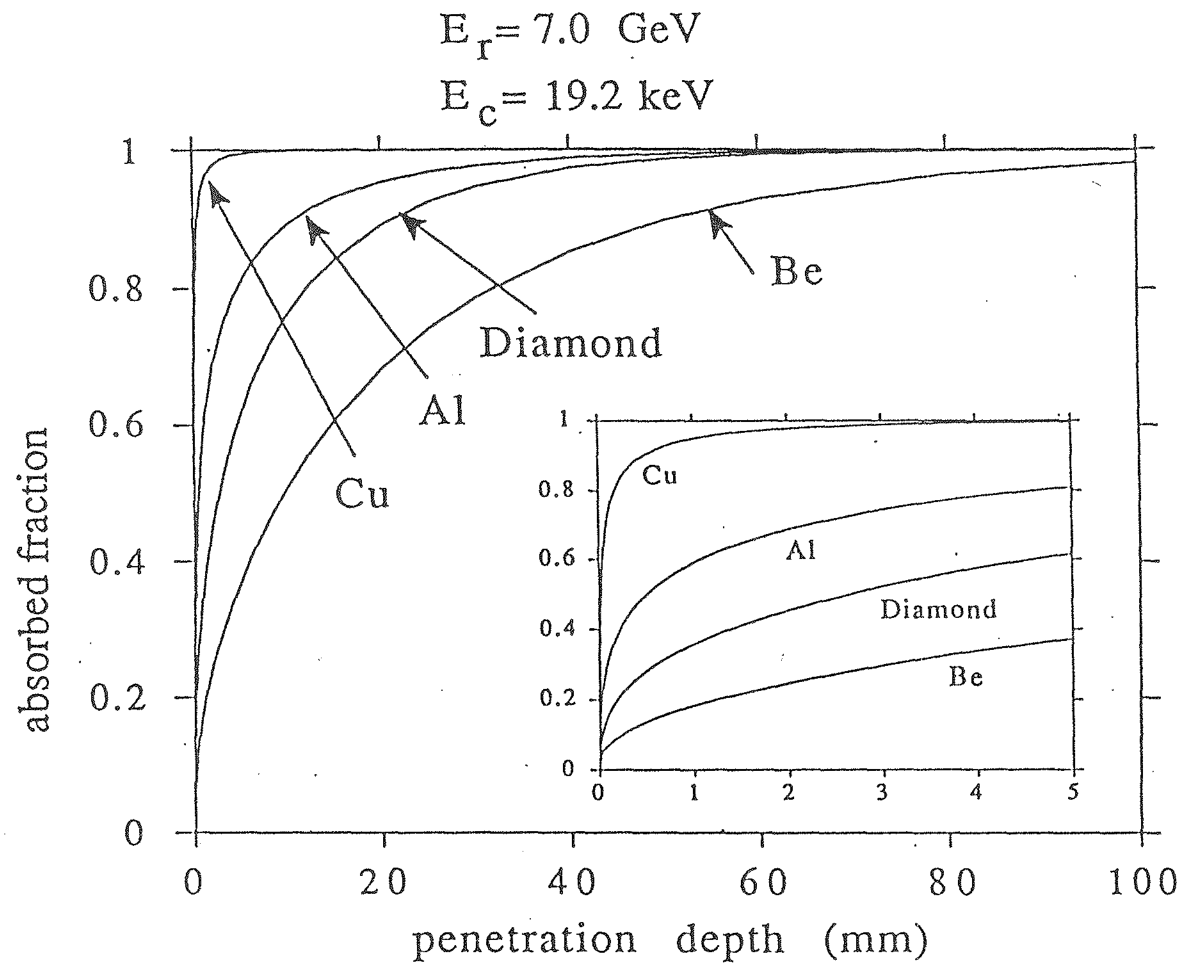


Figure 6: APS bending magnet absorption in various materials. The inset details the profiles for small depths.

footprint. Such fine meshing is also necessary to accurately describe the vertical Gaussian profile of the incident beam.

Since the bending magnet radiation has a slowly varying horizontal profile, it is sufficient, for all practical purposes, to model a vertical strip of the absorber wall as discussed earlier (i.e., a 2-D analysis). The strip is 14 cm long and has a unit width (1 cm). An effective heat transfer coefficient on the cooled side of the absorber plate is used to adequately account for the proposed channel cooling of the absorber wall shown in Figure 2. A three dimensional model is not warranted at this stage since it is unnecessary, expensive to analyse, and adds little to a basic understanding and design of the crotch.

A typical meshing scheme for a vertical strip of the absorber plate is shown in Figure 5, where the plate is inclined at 45° with respect to the incident beams. The length of the plate strip is divided into as many as 100 segments and its depth into about 80 layers. There are typically between 4000-8000 elements. The non-uniformity of the element sizes and the number of elements used in each case reflect the necessary detail to obtain accurate results.

11. Numerical Results

The finite element results for a variety of absorber wall configurations and inclination angles are summarized in Table 3 and they are briefly discussed here. This detailed finite element analysis confirms the basic results of one-dimensional analysis of the previous sections.

In most (but not all) the cases analyzed the absorber plate thickness is 2 cm. The total power of the incident beam on the 1-cm wide strip is 1358 W. The vertical extent of the beam footprint is 6σ (3σ on each side of the

Table 3: Summary of the thermal Analysis Results

Case	Wall Composition	incident power (W/cm)	h W/cm^2-K	Angle of inclination (degrees)	T_{max} Front (°C)	T_{max} Interface (°C)	T_{max} Cooled wall (°C)
A1	2-cm thick Cu layer	1358	1.2	90	859	NA	160
A2	2-cm thick Cu layer	1358	12	60	844	NA	162
A3	2-cm thick Cu layer	1358	1.2	45	823	NA	164
A4	2-cm thick Cu layer	1358	1.2	30	792	NA	175
A5	2-cm thick Cu layer	988	1.2	90	618	NA	118
A6	2-cm thick Cu layer	988	1.2	30	570	NA	128
B1	2-cm thick Cu layer	1358	2.4	30	721	NA	103
B2	1-cm thick Cu later	1358	1.2	30	773	NA	247
B3	3-cm thick Cu layer	1358	1.2	30	875	NA	223
B4	1-mm thick diamond layer on 1.9-cm thick Cu layer	1358	1.2	30	413	422	165
C1	0.5-cm thick Be layer on 1.5-cm thick Cu layer	1358	1.2	90	670	588	177
C2	0.5-cm thick Be layer on 1.5-cm thick Cu layer	1358	1.2	60	669	560	177
C3	0.5-cm thick Be layer on 1.5-cm thick Cu layer	1358	1.2	30	643	467	181
C4	1-cm thick Be layer on 1-cm thick Cu layer	1358	1.2	90	732	482	199
C5	0.5-cm thick Be layer on 2-cm thick Cu layer	1490	1.2	90	758	659	166
D1	2-cm wide 1-cm thick Be block in a 2-cm thick Cu layer	1358	1.2	90	672	454	182
D2	2-cm wide 0.5-cm thick Be block in a 2-cm thick Cu layer	1358	1.2	90	647	572	170
D3	1-cm wide 1.0-cm thick Be block in a 2-cm thick Cu layer	1358	1.2	90	594	436	176
D4	1-cm wide 1.0-cm thick Be block in a 2-cm thick Cu layer	1358	1.2	45	610	370	171
D5	1-cm wide 1.0-cm thick Be block in a 2-cm thick Cu layer	1358	1.2	30	632	303	164
D6	1-cm wide 1.0-cm thick Be block in a 2-cm thick Cu layer	1358	2.4	30	542	241	97

beam center, where σ is the standard deviation of the vertical Gaussian profile of the incident beam). The plate is assumed to be adiabatic at both ends. The absorption profiles of the APS bending magnet radiation in copper, aluminum, diamond and beryllium is obtained from the Photon Program [3]. They are shown in Figure 6 and are used in the study.

The first four sets of thermal results in Table 3 (A1 to A4) are for a 2-cm thick copper plate with different inclination angles with respect to the incident beam direction. The temperature profiles for an inclination angle of 45° (case A3) are shown in Figures 7a and 7b. The maximum temperatures of the plates (at the beam footprint) ranges from 859 for θ=90° (i.e., normal incidence) to 792° C for the plate at 30° with respect to the beam. These results differ by as much as 200° C from earlier published results which now appear to have been due to an inadvertent error [4]. Even at 30° inclination, the maximum temperature of 792° C far exceeds our design criterion of 300-350° C for copper. Smaller (grazing) angles are not considered since they will result in an elongated crotch compartment. The maximum temperature of the cooled surface of the absorber plate, henceforth simply referred to as the cooled surface, for these four cases range from 160 to 175° C. The maximum temperature is located closer to the top of the plate (Figure 6) because of the asymmetry of the absorber plate with respect to the normal at the footprint. From Figure 7b which shows a typical wall temperature profile, it is clear that localized boiling will occur. To prevent boiling in this case, water must be pressurized to about 10 atmospheres.

In Cases A5 and A6, the temperatures are computed for the copper plate when it is moved from a distance of 1.92 m distance from the BM source to 2.25 m, leading to a reduction from 1358 to 988 W/cm beam power.

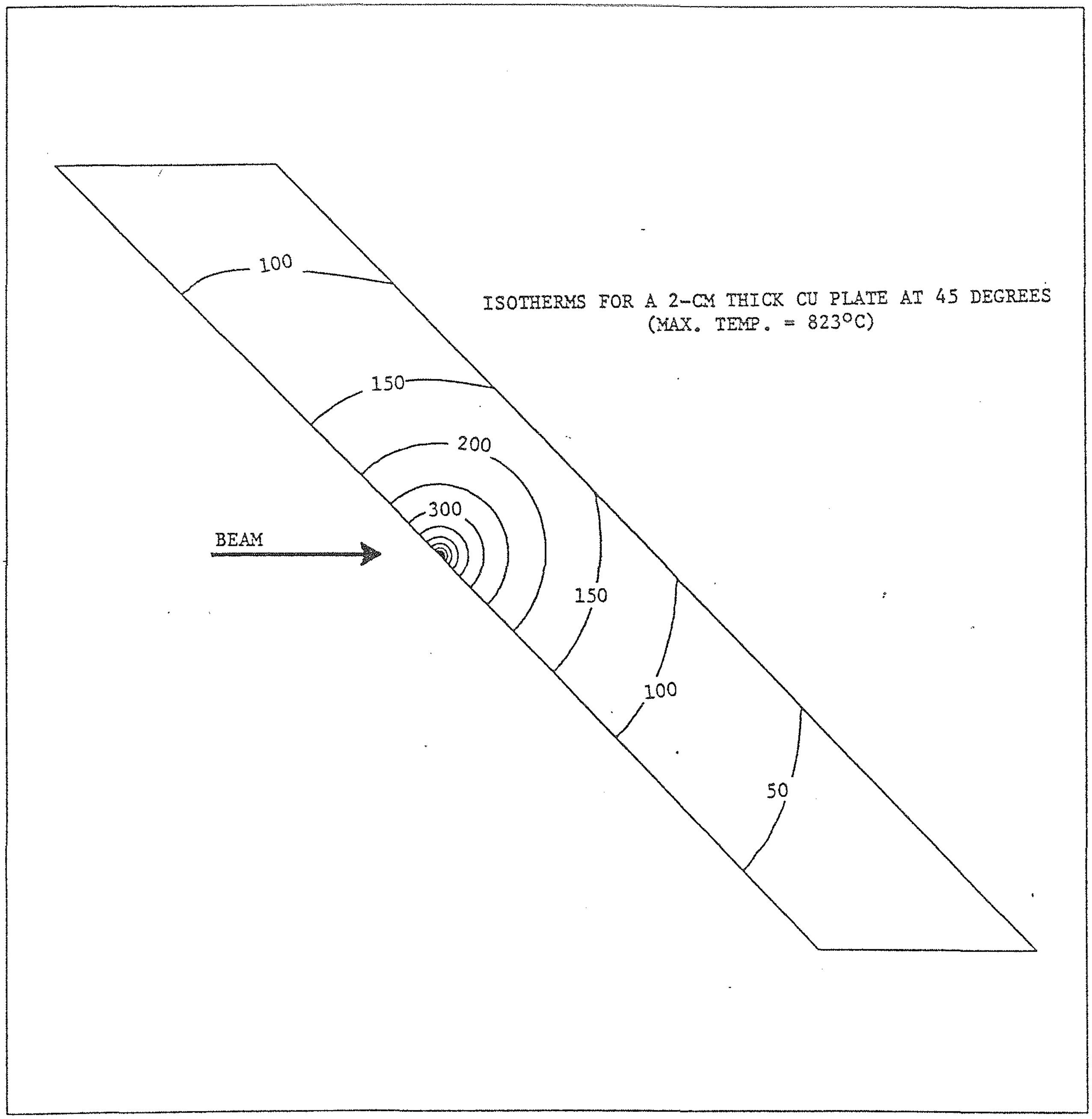


Figure 7: (a) Temperature distribution in a 2-cm copper plate (case A3, Table 3), and (b) temperature on the front and back wall of the plate. The angle of inclination is 45°.

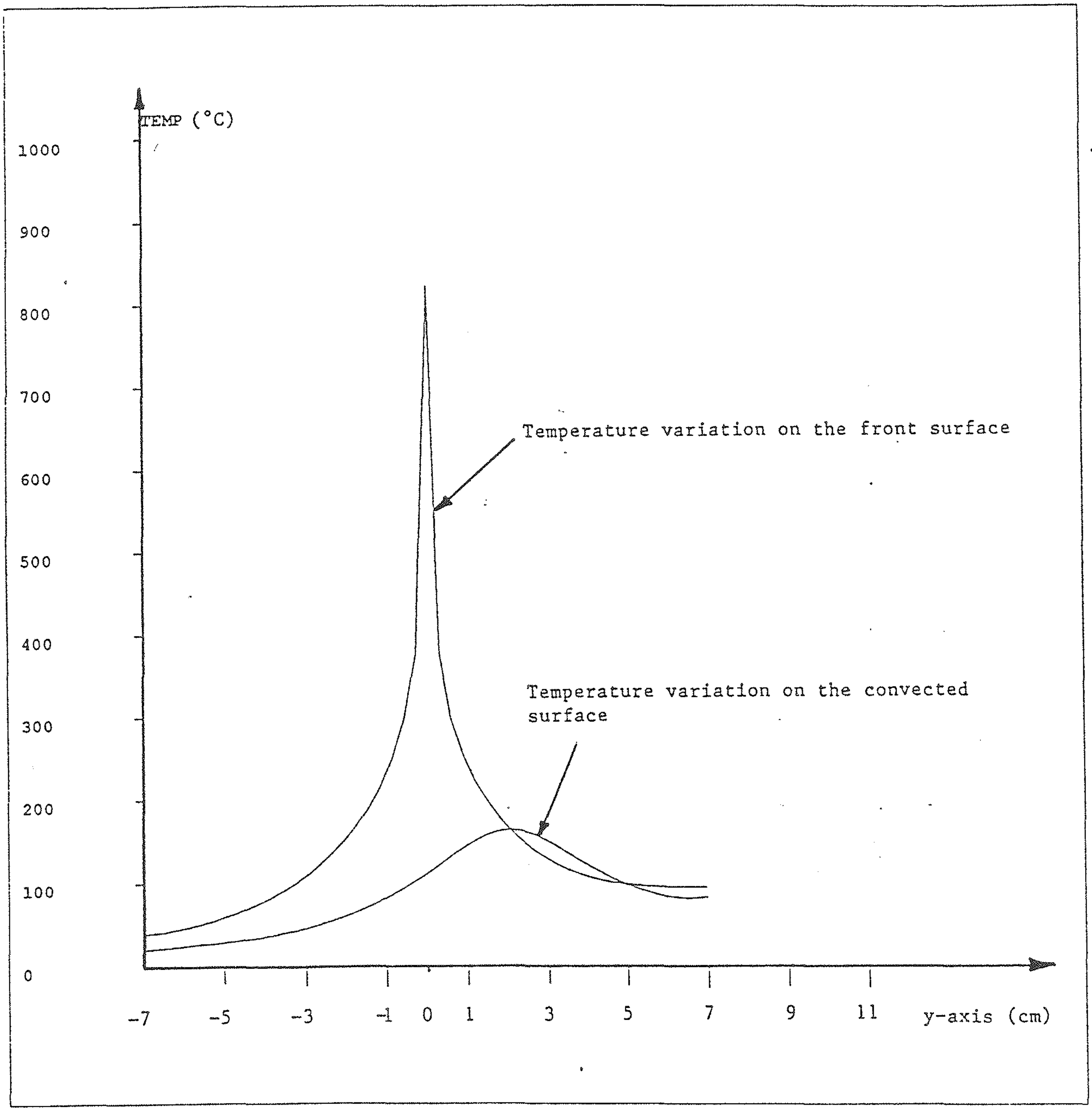


Figure 7b: See legends under Figure 7.

In the next case studied (case B1) we have doubled the heat transfer coefficient to 24,000 W/m^2K, a representative value to allow for partial subcooled boiling at the cooled surface [5]. (This is a crude treatment of the problem since for an accurate description a heat transfer coefficient distribution dependent on the local wall temperature must be used.) The maximum temperature of the cooled surface is reduced from 175 to 103. Thus, if high water pressure is to be avoided, a lower water pressure allowing for partial subcooled boiling provides a reliable and attractive choice. (Subcooled boiling is characterized by formation of bubbles at the heated surface followed by their condensation on in the cool liquid away from the wall so that there is no net vapor generation in the coolant flow. This latter feature is the main reason why subcooled boiling is preferred in many applications.)

Case B1, furthermore, is in accord with the one-dimensional model results in that enhanced heat transfer coefficient predominantly affects the temperature of the cooled surface. Doubling the heat transfer coefficient reduced the maximum temperature in the absorber plate only marginally, from 792 to 721° or about 9%, while the maximum temperature of the cooled surface is reduced by 41%. Thus, more efficient cooling methods (i.e., higher h) by itself does not reduce the maximum temperature of the absorber plate appreciably.

Cases B2 and B3 in Table 3 examine the effects of wall thickness. As expected (Eq. 3b) a thinner plate will have a lower maximum temperature.

Case B4 of Table 3 shows that a 1 mm thick layer of diamond deposited on a 19 mm thick copper plate reduces the maximum temperature of plate from 792 to 422° C. This can be accomplished by chemical vapor deposition (CVD), an active research area at the present. The sharp reduction in plate temperature results from very high thermal conductivity of diamond, a feature that may find applications elsewhere at APS.

The next four cases considered (C1 and C4 in Table 3) examine the thermal behavior of a composite Be-Cu wall. Note that the total thickness of the wall is still 2 cm, and the maximum plate temperature in every case is at the beam footprint on the front surface of the Be layer. For beryllium, temperatures in the 500-600° C range are acceptable but the maximum temperature of the copper segment which occurs at the Be-Cu interface is still too high even at 30° inclination angle (Case C4).

Case C5 in Table 3 represents a 2.5 cm composite be-Cu plate which is located 1.75 cm from the BM source. Note that in this case also the maximum temperature occurs at the beryllium surface.

As discussion in detail earlier, the purpose of the Be attachment is to attenuate the bending magnet radiation gradually. Thus considering the lower thermal conductivity of Be in comparison with copper, it is desirable to replace the Be layer with a smaller piece which is wide enough to cover the footprint of the incident beam. This problem was analyzed and the results are included in Table 3. Case D1 shows that replacing the 1-cm thick Be layer by a 2-cm wide, 1 cm thick block leads to reductions in the maximum temperatures from 732 to 672° in beryllium, and from 482 to 454° C in copper. A shorter beryllium piece (Case D3) reduces these temperatures farther. If in addition the plate is inclined with respect to the incoming beam a further reduction in the maximum temperature is obtained. At 30° inclination (Figure 8a), the maximum temperature of Be is 632° C, and that of copper at the Be-Cu interface is 303° C (Case D5). These are within our target temperatures and this case can be used as a basis for more detailed analysis. The temperature profiles for this case are shown in Figure 8b, c, and d. Case D6 of Table 3 details

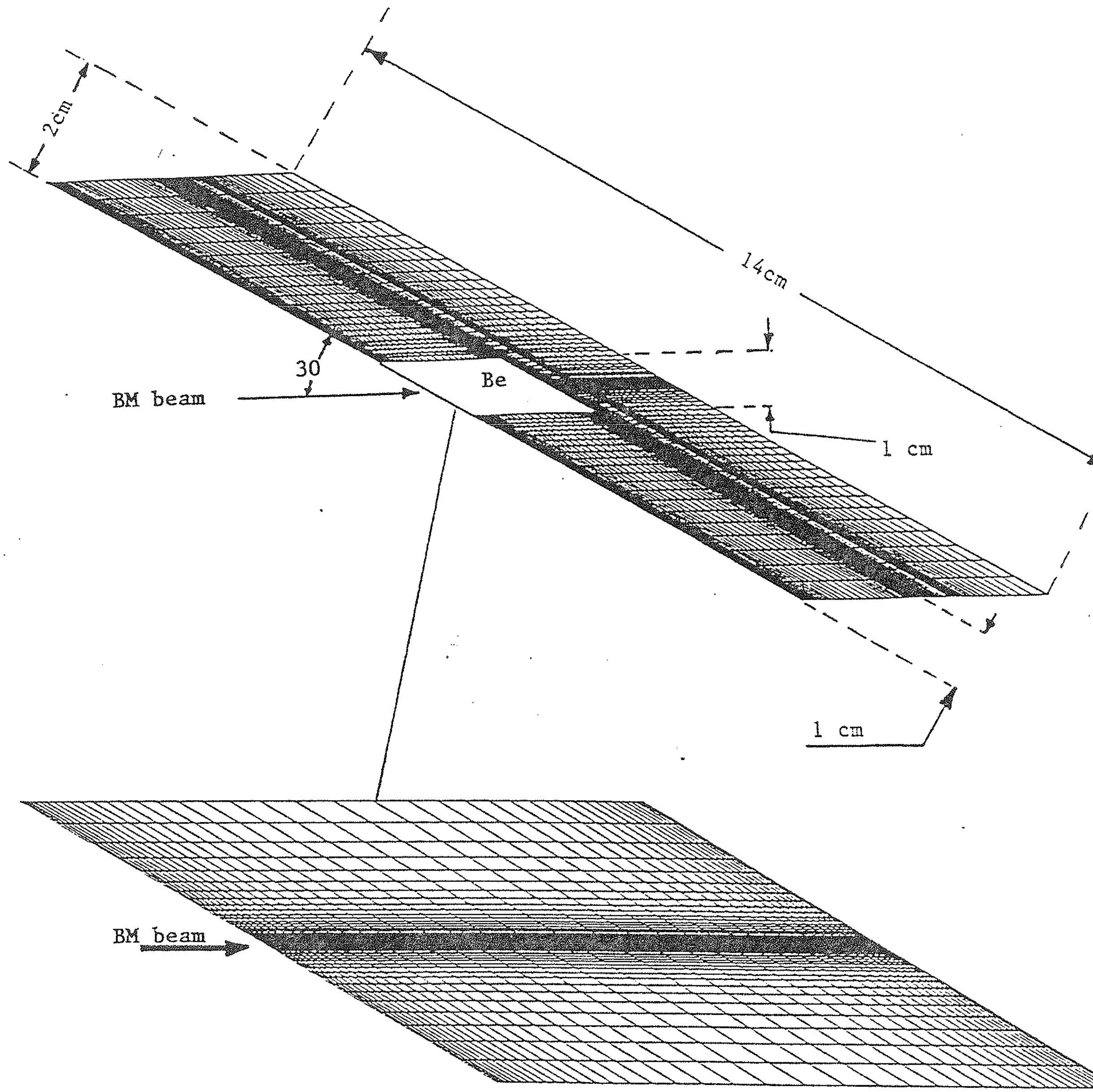


Figure 8: (a) The meshing scheme for a copper absorber plate with a berylium block insert, inclined at 30° angle with respect to the incident BM beams and (b, c, and d) temperature distribution in the plate.

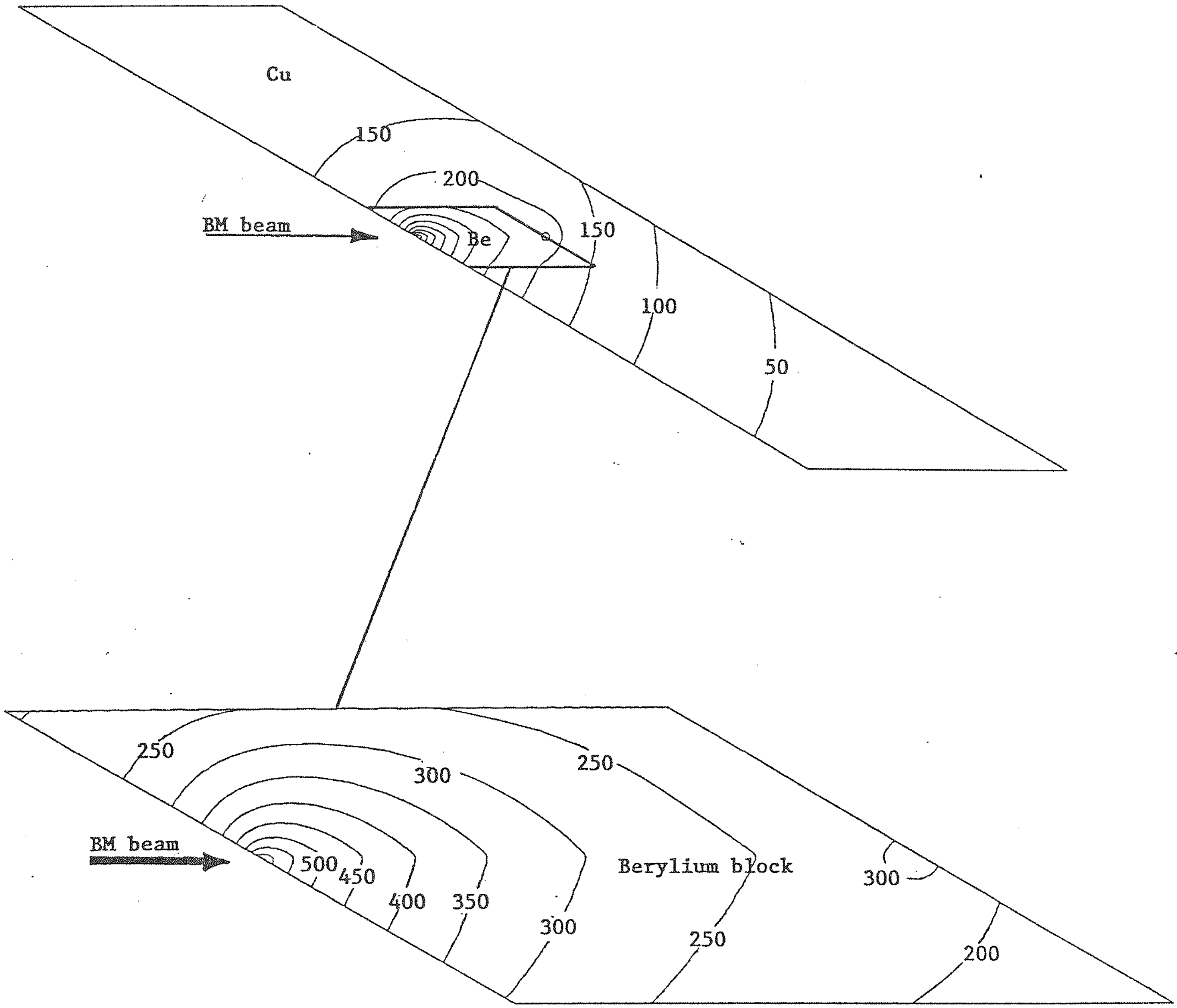
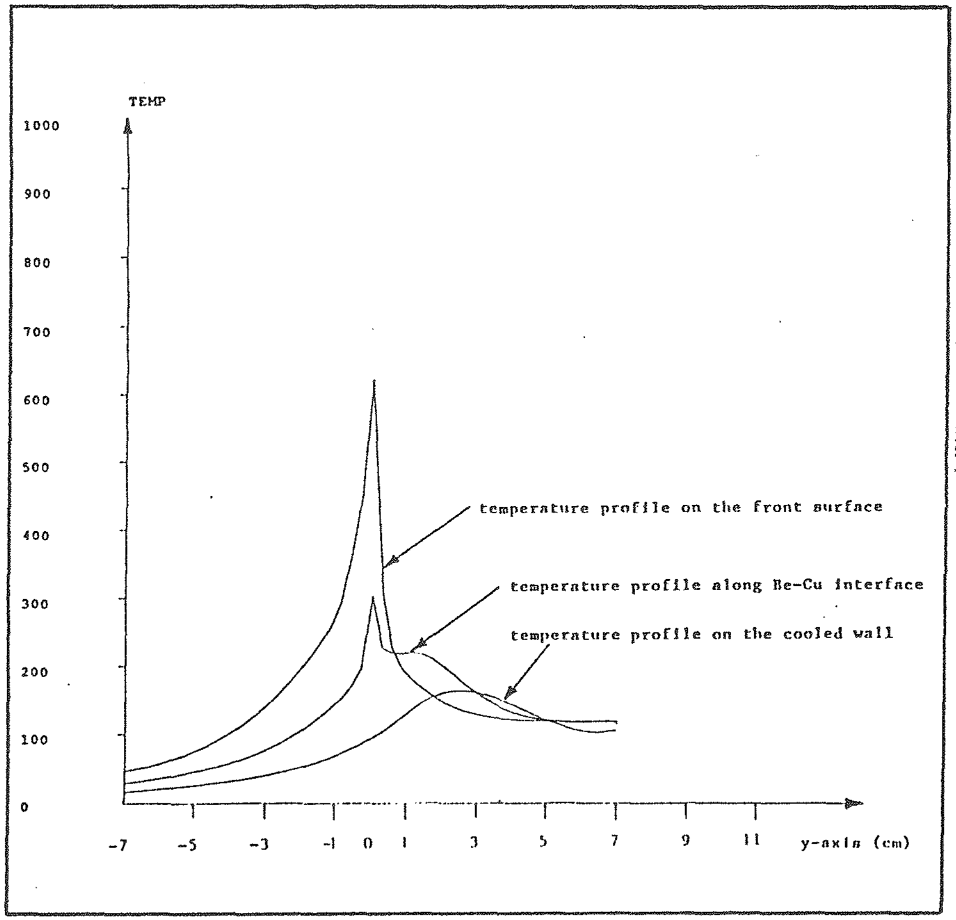
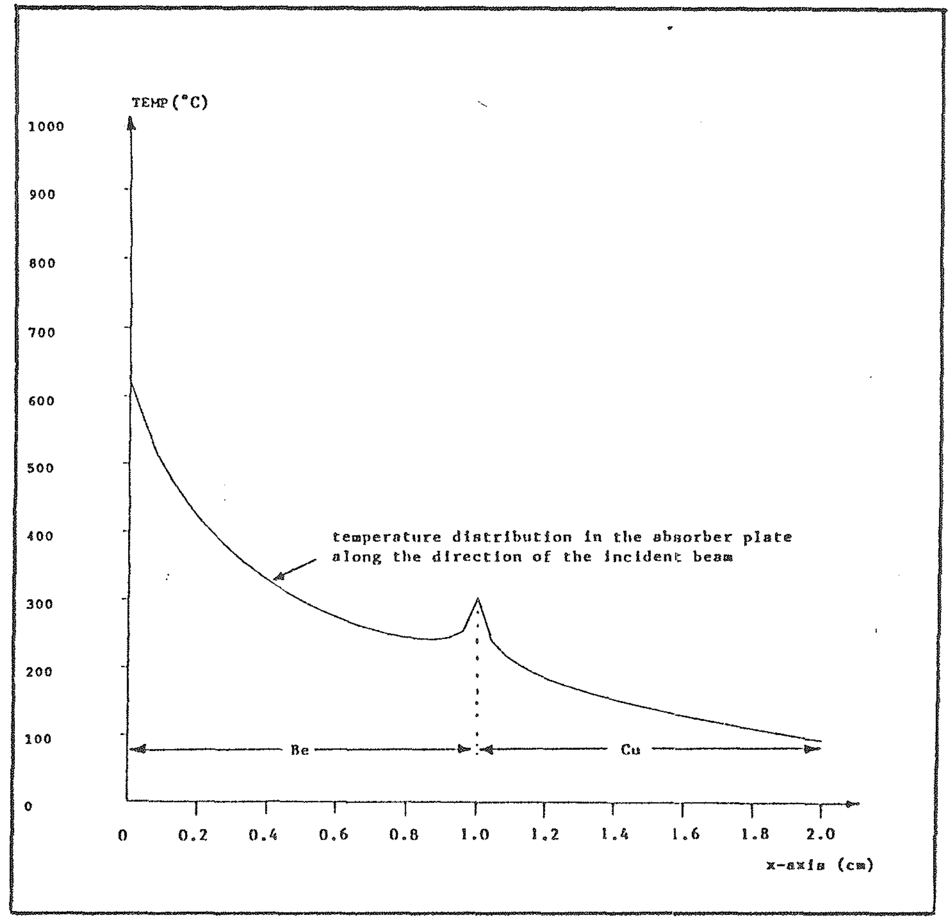


Figure 8b: See legends under Figure 8.





Figures 8c (right) and 8d (left): See legends under Figure 8.

the relevant temperatures if a high heat transfer coefficient of 24,000 X/m-K is used. This is attainable, as mentioned earlier, by subcooled boiling (in which case inlet water temperature must be raised above the current 5°C).

12. Summary, Conclusions, and Recommendations

On the basis of the preliminary analysis reported here a number of broad conclusions can be drawn as summarized below. In addition, several alternative design approaches are suggested that may further be investigated.

1. Most of the thermal analysis results reported here reflect an incident power of 1358 W on a 1 cm-wide strip of the absorber plate. This is the maximum incident power per unit horizontal length at 1.92 m from the BM source which diminishes to about 700 W/cm at the other end of the footprint. Thus, somewhat lower temperature can be expected in a full three-dimensional analysis.

2. The results of the 2-D finite element analysis reported in this study are accurate to within 10°C. Temperature dependency of material properties has been included in the analysis. Note that lower plate temperatures are expected if the adiabatic boundary conditions imposed on both ends of the absorber plate are relaxed.

3. For a copper based crotch, the use of a diathermanous material (such as beryllium) is imperative to attenuate BM radiation sufficiently to prevent unacceptably high temperatures on copper plate. This attachment should only be wide enough to completely intercept the beam and thick enough to absorb at least 50% of the incident beam (see Figure 8a).

4. The developing technique of chemical vapor deposition (CVD) has opened a new avenue to a large number of cooling problems. While the possibility and suitability of this technique in the crotch design is currently questionable, a 1-2 mm layer of diamond mounted or deposited on a copper absorber plate will be adequate to reduce the plate temperature to within acceptable range.

5. The possibility of using beryllium alloys as the absorber plate or the crotch material may exist, eliminating the need for a diathermanous attachment [6].

6. Design of an all Be crotch should be given serious consideration. Be has high mechanical strength and relatively high thermal conductivity. Standard hot vacuum presenting (and outgassing) of Be powder into fine-grain ductile and easily machinable metal which can be rolled, drawn, or extruded is commercially available. Near-net shape blanks can be produced which are then finished with minimal machining. At about $400/Lb, a 15x15x10 cm^3 hollow block of Be with an average wall thickness of 3 cm will cost about $5,000. Pressing and machining costs and addition of a heavy metal shield on the exterior of the chamber must be added. An important feature of this design is that cooling channels can be extruded during the hot vacuum pressing. Water flowing in these channels can absorb a portion of incident BM radiation directly.

7. A variation to the approach above is to fabricate only the absorber plate from Be as described. Or alternatively a thick Be piece with pre-fabricated cooling channels can be sandwiched in the copper wall as shown in Figure 9a.

8. An attractive feature of using a sandwiched Be block is that cooling channels and/or porous inserts can be configured such that a large portion of incident BM radiation is directly absorbed by the water flowing through the channels. Thus possibility exists to avoid boiling and also substantially reduce the overall plate temperature by proper configuration of the cooling channels in the beryllium piece (Figure 9b).

9. Utilization of high boiling point coolants in a closed loop may also be considered as an option for single phase heat transfer [7].

10. The suggested design in this study outlined in Section 11 (Case D5 in Table 3) reduces the overall temperature of the absorber plate to manageable levels, however, under atmospheric pressure the (chilled) cooling water will boil.

11. If boiling of water is to be prevented, a combination of higher fluid pressure, flow rate, and heat transfer augmentation techniques must be used. The latter includes extended surfaces (sketched in Figure 9c), rough surfaces, swirl flow provisions, injection, suction, etc. A very promising technique that is ideally suited for hot spot cooling such as in

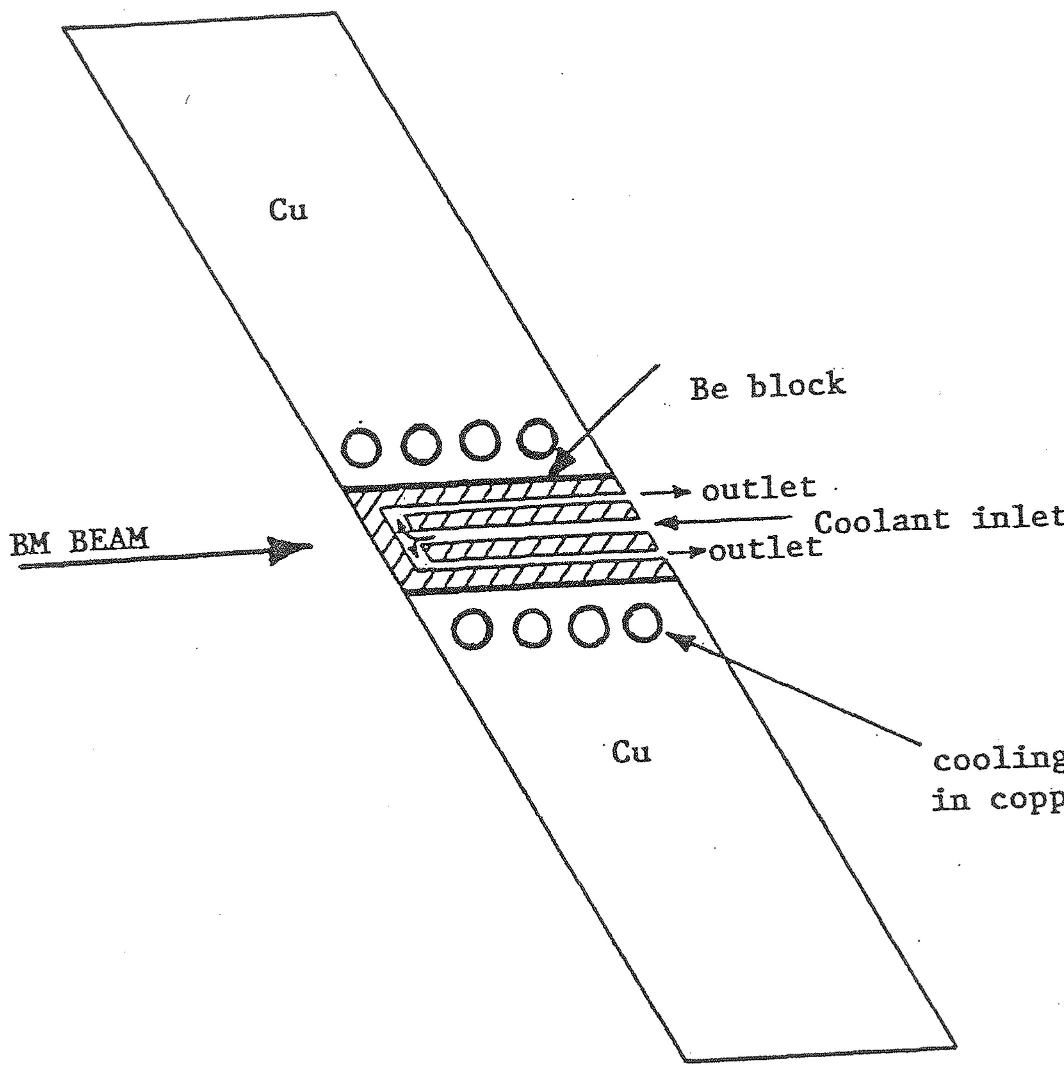


Figure 9: (a) Pre-fabricated cooling channels in a thick Be piece sandwiched in the copper absorber bar, (b) Be piece with internal porons structure, (c) use of extended surfaces (in this case flow is into the paper), and (d) jet impingement scheme for efficient cooling.

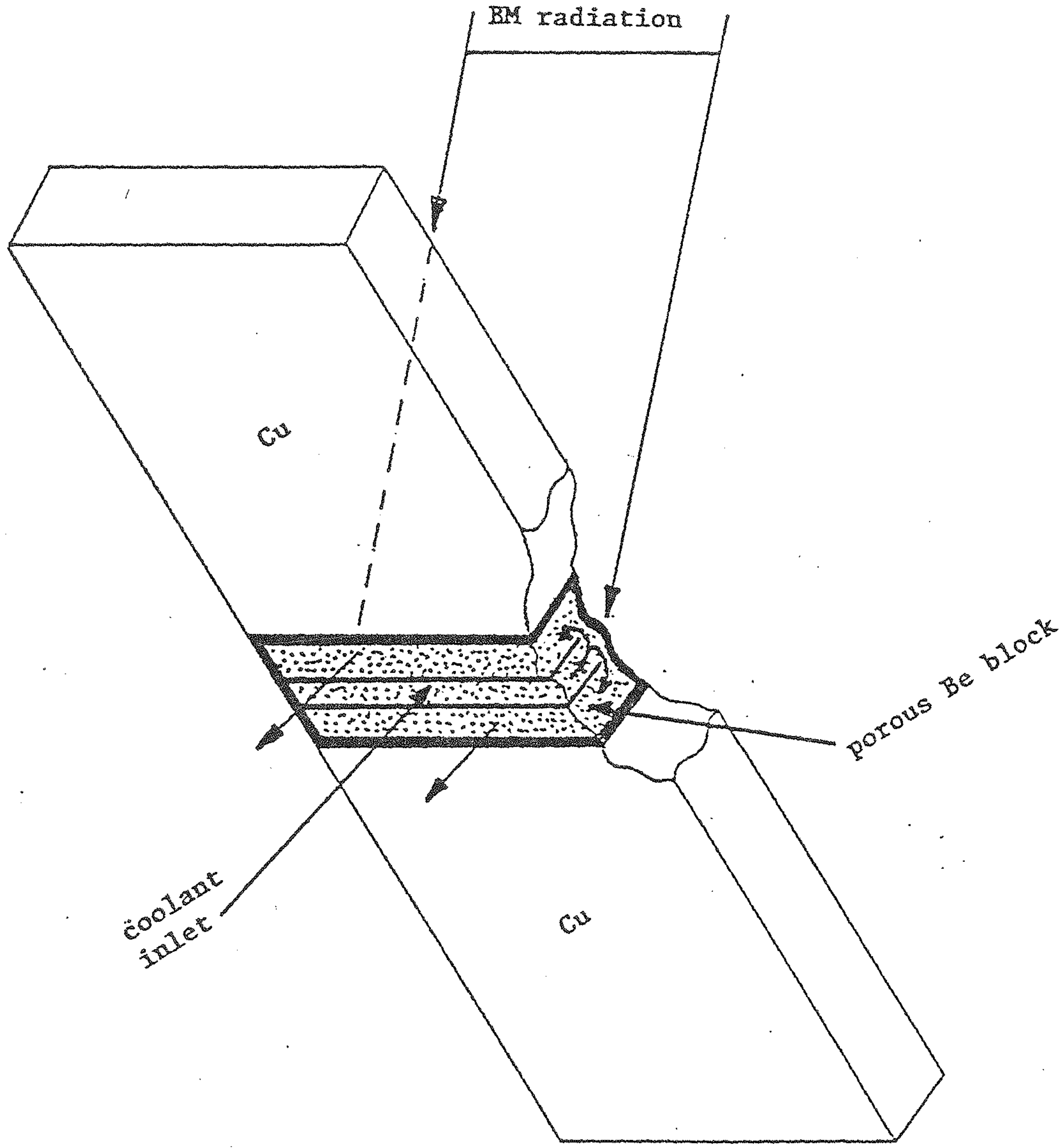
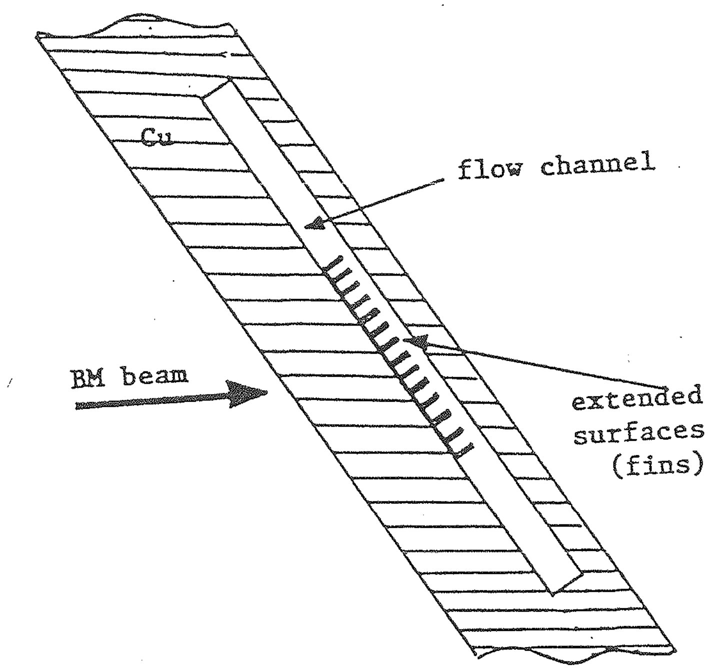


Figure 9b: See legends under Figure 9.



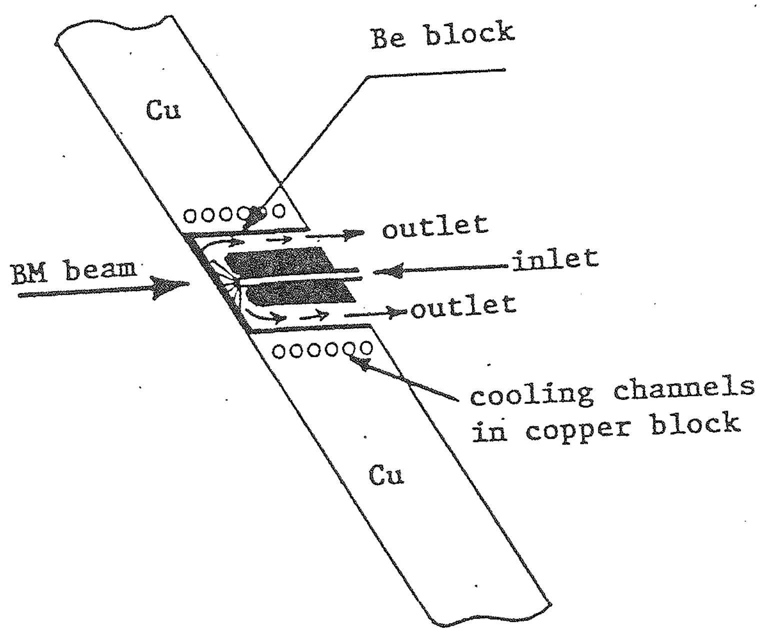


Figure 9c (above) and 9d (below): See legends under Figure 9.

the present problem is jet cooling that may be considered (sketched in Figure 9d). It is recommended that jet cooling be given serious consideration.

12. If boiling heat transfer regime is acceptable, then a combination of water bulk temperature, pressure, and flow rate can be used to assure subcooled heat transfer (Case D6 in Table 3) The flow will essentially remain single phase.

13. All thermal analysis reported in this study are for steady state conditions. Thermal transient analysis may be carried out to rule out the remote possibility that rapid application of the bending magnet radiation may cause thermal shock in the absorber material giving rise to temperature gradients larger than the study state valves. Because of the application of severe and rapid stress in the case of thermal shock, the thermal shock resistance of the crotch material (which may depend on the time rate as well as the magnitude of induced stress) should be investigated.

14. Fluctuating thermal stresses in the absorber plate material resulting from successive heating up and cooling-down of the crotch in the course of its operation can lead to thermal fatigue [8]. A thermal stress (elastic) analysis of the problem will give the stresses in the system that can be used to estimate the number of cycles that the material can endure before failure due to crack initiation and propagation. This examination has not been included in this preliminary analysis.

13. Acknowledgement

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